NANOFLUID HEAT TRANSFER PHENOMENA THROUGH POROUS MEDIA

SYNOPSIS

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1 Introduction

All the materials show some level of deformity under the action of applied forces. A material is said to be fluid if there is a continuous increase in the deformation of that material without limit under the action of applied strong forces. Science which concerned with the behaviour and properties of the fluids which are in motion is termed as “Fluid Dynamics" [1]. There are numerous practical situations where the study and the principles of fluid dynamics played a vital role e.g. in flight of aircraft, ship science, effect of air and winds on buildings, ground water seepage, extraction of ground water, extraction of oil, etc. Fluid dynamics is an imperative branch of applied sciences in view of its theoretical and practical applications. Apart from the academic interest, this subject find its importance in our day to day life. The study of fluid dynamics is highly important to a physicist to understand the wave phenomena in the oceans and in the earth’s surroundings. Engineers find the use of this subject in solving the industrial problems. Aerospace engineers find its usefulness in the designing of the aircraft that possess high lifts along with small resistance. A Civil engineer employee the principles of fluid dynamics for the water supply systems, irrigation canals, formations of the dams and many more. Fluid coupling, designing of turbines and heat ex-changers are some processes where mechanical engineers implicated the principles of this subject. Hence, it is very much essential to understand the fundamental of fluid flows for the designing of such systems in which flows of the fluids are working media.

Flow of the fluids and their behaviour follow some certain laws of nature such as conservation principles of mass, momentum and energy. Differential forms of these laws can be easily stated at a point in the form of equation of continuity, Navier-Stoke’s equations (i.e. equation of motion) and equation of energy. Tensor form of these equations for the viscous compressible flow of fluids are described below:

Equation of state

$$pV = nRT, \tag{1}$$

where, p is pressure, V is volume, n is the amount of substance, R is ideal gas constant and T is the temperature.

Conservation of mass

The integral form of the continuity equation is:

$$\frac{\partial}{\partial t}\int_v \rho dv = -\oint \rho u.nds, \tag{2}$$

In this equation L.H.S. of the equation represents the rate of change of mass in control volume and R.H.S. represents the inflow of the mass from the surface of the control volume. It can be also written as:

$$\int_v \left\{ \frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{u}) \right\} dv = 0, \tag{3}$$

If the integrand of this equation is equal to zero, then this equation is valid for all types of control volume. Then equation (3) becomes:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{u}) = 0, \tag{4}$$

$$\frac{1}{\rho}\frac{\mathbf{D}\rho}{\mathbf{Dt}} + \nabla.\mathbf{u} = 0, \tag{5}$$

where, $\dfrac{\mathbf{D}}{\mathbf{Dt}} = \left(\dfrac{\partial}{\partial t} + u\dfrac{\partial}{\partial x} + v\dfrac{\partial}{\partial y} + w\dfrac{\partial}{\partial z}\right) = \dfrac{\partial}{\partial t} + \mathbf{u}.\nabla$ is the material derivative.

Conservation of momentum

$$\rho\frac{\mathbf{D}}{\mathbf{Dt}}(v_i) = \rho f_b - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{ \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\frac{\partial v_k}{\partial x_k}\delta_i j \right) \right\}, \tag{6}$$

where, $\dfrac{\mathbf{D}}{\mathbf{Dt}} = \left(\dfrac{\partial}{\partial t} + v_j\dfrac{\partial}{\partial x_j}\right)$ is the material derivative and $i, j = 1, 2, 3$.

Conservation of energy

$$\rho\left[\frac{\partial h}{\partial t} + \nabla.(h\mathbf{V})\right] = -\frac{Dp}{Dt} + \nabla.(k\nabla T) + \beta, \tag{7}$$

where, h is the specific enthalpy which is related to the specific internal energy as $h = e + p/\rho$. T is the absolute temperature and β is the dissipation function representing the work done against viscous forces, which is irreversibly converted into internal energy.

The governing equations for the flows of viscous in-compressible fluids take the following form discussed below:

Conservation of mass

$$\nabla.\mathbf{u} = 0, \tag{8}$$

Conservation of momentum

$$\rho \frac{\mathbf{D}}{\mathbf{Dt}}(v_i) = \rho f_b - \frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 v_i}{\partial x_j \partial x_j}, \tag{9}$$

Conservation of energy

$$\rho c_p \left[\frac{\partial T}{\partial t} + (\mathbf{V}.\nabla)T \right] = k\nabla^2 T + \alpha, \tag{10}$$

where, c_p is the specific heat at constant pressure.

1.1 Nanofluids and their models

Nowadays in many technological and industrial processes where we have to maintain heating and cooling, and for this purpose we need a fluid that can transfer heat and mass more prominently and efficiently than conventional fluids [2]. Traditional fluids have poor coolent properties which leads to limited and controlled heat transfer. In order to break this short coming of limited heat transfer, scientists and engineers made plenty of efforts in this direction. Addition of the solid particles in the base fluids [3] was one of the suggested approach to enhance the heat transfer rates because solids has superior thermal conductivity [4] than liquids. In view of this Maxwell [5] gave the idea of suspension of mirco sized particles in the base fluids and the result was enhanced rate of heat transfer. But this suspension leads to plenty of complications like settling of these particles in carrier liquid, increased pressure drop and enhanced thermal resistance. After this Masuda et al. [6] realized intensification in the thermal conductivity of fluids after addition of submicronic particles but it also had some drawback like settling and agglomeration of the submicronic particles in fluid. Eventually, Choi [7] dispersed the nanoparticles in the base fluids and break the shortcoming of suspensions done by Maxwell [5] and Masuda et al. [6]. It was Choi who pioneered the name “Nanofluid" for this new class of heat transfer

fluids. The challenges such as agglomeration and settling of particles by virtue of gravity are overcome due to brownian motion of suspended nanometre sized particles. Nanofluid are engineered fluids in which solid particles of size less than 100nm are suspended in base fluids and these particles concentration should be less than 0.5 volume percent. The choices of the base fluids and nanoparticles utilized for the synthesis of nanofluids totally depends upon the applications for which the nanofluids are being prepared. One can use water or any other organic solvent as base fluids and nanoparticles are made up of metal and their oxides. Wide literature is available which shows that the usefulness of using nanofluids as a coolant for various applications where heat transfer is required. Nanofluid find its applications [8] as a coolant in microelectronic cooling industries, automobiles engine cooling, nuclear reactors cooling, solar reflectors, etc. Commonly, Tiwari and Das nanofluid model [9] and Buongiorno nanofluids model [10] are utilized to examine the convective heat transmission in naofluids. The briefing about these models are given below:

1.1.1 Tiwari and Das nanofluid model

This nanofluid model is conferred by Tiwari and Das [9] and is also termed as either homogeneous nanofluid flow model or single component flow model because nanofluids act like liquids. In this model, Tiwari and Das concluded that improvement in the heat transfer characteristics of nanofluids is basically due to incremented thermal conductivity of fluids. Following are the conservation equations for the flow of nanoliquids structured by Tiwari and Das [9] nanofluid model:

- Continuity Equation:

$$\nabla.\mathbf{u} = 0, \tag{11}$$

- Momentum Equation:

$$\rho_n \frac{\mathbf{Du}}{\mathbf{Dt}} = -\nabla P + \mu_n \nabla^2 \mathbf{u}, \tag{12}$$

- Energy Equation:

$$(\rho c_p)_n \frac{\mathbf{DT}}{\mathbf{Dt}} = \nabla \cdot \kappa_n \nabla T. \tag{13}$$

Here, effective viscosity of nanofluids is given below

$$\mu_n = \frac{1}{(1-\phi)^{2.5}}, \tag{14}$$

effective density of nanofluids can be expressed as

$$\rho_n = (1-\phi)\rho_f + \phi\rho_p, \tag{15}$$

heat capacitance of nanofluids is given below

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_s, \tag{16}$$

whereas the effective thermal conductivity of nanofluids is calculated by using the following relation

$$\frac{\kappa_n}{\kappa_f} = \frac{k_s + (l-1)k_f - (l-1)\phi(k_f - k_s)}{k_s + (l-1)k_f + \phi(k_f - k_s)}, \tag{17}$$

where, $l = 1.5$ is considered for cylindrical nanoparticles and $l = 3$ is considered for spherical nanoparticles.

1.1.2 Buongiorno nanofluid model

Buongiorno discussed the seven slip mechanisms that can attributed towards the production of the relative velocities between carrier fluids and nanoparticles. But he concluded that out of these seven slip mechanisms only Brownian motion and thermophoresis can produce relative velocity. Brownian motion [11] is the random movements of the particles in the carrier liquid and the mass flux due to Brownian motion is calculated by

$$\mathbf{j}_{p,B} = -\rho_p D_B \nabla\phi, \tag{18}$$

Thermophoresis is a phenomenon of diffusion of nanoparticles with a change in temperature and the mass flux due to this thermophoretc effect is

$$\mathbf{j}_{p,T} = -\rho_p D_T \ \mathbf{V} = -\rho_p D_T \frac{\nabla \mathbf{T}}{\mathbf{T}}, \tag{19}$$

On combining equation (18) and (19), we get $\mathbf{j}_p$, which is diffusive mass flux of

nanoparticles. Mathematically the expression for j_p can be written as:

$$\mathbf{j}_p = \mathbf{j}_{p,B} + \mathbf{j}_{p,T} = -\rho_p D_B \nabla\phi - \rho_p D_T \frac{\nabla T}{T}, \tag{20}$$

Conservation equations for Buongiorno nanofluid model

The nanofluid continuity and momentum equation for incompressible nanofluid remains the same as defined in equation (8) and (9). The conservation equations for the flow of nanofluid in Bourgino nanofluid model has been explained below.

Nanoparticles continuity equation:

$$\frac{\mathbf{D}\phi}{\mathbf{Dt}} = -\frac{1}{\rho_p}\nabla\mathbf{j}_p, \tag{21}$$

where, $\mathbf{j}_p$ is diffusive mass flux for nanoparticles which is composite by brownian diffusion $\mathbf{j}_{p,B}$ and thermophoresis diffusion $\mathbf{j}_{p,T}$,

Conservation of energy for the nanofluid is defined as:

$$(\rho c_p) f \frac{\mathbf{D}T}{\mathbf{Dt}} = \nabla.k\nabla T - c_p\,\mathbf{j}_p.\nabla T, \tag{22}$$

When we substitute the value of equation (20) in equation (22), then the above equation becomes:

$$(\rho c_p) f \frac{\mathbf{D}T}{\mathbf{Dt}} = \nabla.\, k\,\nabla T + \rho_p\, c_p \left[D_B\,\nabla\phi.\nabla T + D_T \frac{\nabla T.\nabla T}{T} \right]. \tag{23}$$

Equation (23) is the final form of the energy and it shows that nanoparticles diffusion plays an important role in transportation of heat together with convection and conduction.

1.2 Porous Medium

Flow of the fluids through porous media are highly significant and prevalent in our daily lives. Hence analysis of such kind of flows is of great significance in number of engineering and scientific applications. This kind of study find its usefulness in petroleum industries, which are concerned with the analysis of flow, heat and mass transfer of the movements

of oil through the porous rocks. This kind of study also finds its applications in the paper making processes, filtration processes in chemical industries, underground reservoirs, seepage water in river beds, etc.

Porous medium is specifying by the various geometrical properties. Porosity and permeability are two main geometrical properties of porous materials.

1. **Porosity:** In this property of the porous medium, we will discuss about the certain storage capacity of the medium. Porosity of the porous medium is an indicator in which we see that how much fluid can be stored within the medium. Generally, the simple porosity or the average porosity of the porous medium is define as the ratio of the interconnected pore volume V_P to the total volume (Bulk volume) V_T of any sample. The total volume V_T has solids as well as pore volume.

   Porosity at a point is just a generalization that cannot be measured experimentally. We can measure only the average porosity of the material. Porosity is the important physical characteristics of the porous media which determines the phase flowing volume in the medium or the quantity of oil and water present in problems of petroleum recovery. There are many different methods are available which determine the porosity of the medium.

2. **Permeability:** Permeability is used to measure the fluids passes through the porous material. The specific definition of the permeability is the ability of the medium that how much fluids allow to flow in a porous medium with which it is drenched through its pores. Permeability of the medium is measured by the rate of flow of fluids. If any medium follow these then we can say that the medium is permeable or previous. On the other hand, the medium which cannot easily drench the medium is called impermeable or impervious medium. It is closely related to the degree to which they are interconnected and the size of the voids. In a porous medium if voids are large and interconnected to each other, then the fluids flow freely but if the voids are small and interconnected to each other then fluids move slowly. The permeability is independent of the fluid properties but it depends upon the property of the medium. The units of the permeability are gallon/day/ft, Darcy, m/s, f/s. Permeability "K" may be expressed as:

$$K = -\frac{Q\mu}{A\rho g}\left(\frac{\partial h}{\partial s}\right)^{-1}.$$

Here, Q is the volume of fluid discharged per unit time, A is the cross-sectional area, μ is the viscosity, ρ is the fluid density and $\left(\frac{\partial h}{\partial s}\right)$ is the hydraulic gradient in the direction of flow.

1.2.1 Darcy Model

Henry Darcy [12] in 1856 had opened the ways to study the flow of fluids through porous medium by deriving an equation which is capable to define the ability of the fluids to flow through porous materials. Later, this law is named after his name as Darcy law. After that this law has been used and applied to solve plenty of problems related to the flow through porous materials. One application of Darcy's law is in the analysis of water flow through an aquifer. Darcy's law along with the equation of conservation of mass simplifies the groundwater flow equations. Mathematically, this law is expressed as;

$$\nabla p = -\frac{\mu}{k}\mathbf{u}.$$

Here, p is the pressure gradient, k is the permeability, $\mathbf{u}$ is the velocity vector and μ is the dynamic viscosity.

1.2.2 Brinkman's Model

Darcy's law had a limitation, it was failed to explain if there is any viscous interaction between the particles. Brinkman [13] overcame this limitations of Darcy's law by introducing following mathematical model for the flow of fluid through porous media:

$$-\nabla P - \frac{\mu}{k}\mathbf{u} + \nu\nabla^{\mathbf{2}}\mathbf{u} = \mathbf{0}.$$

Term $\nu\nabla^2\mathbf{u}$ is representing the viscous stress.

2 Review of Literature

Importance of heat transfer in many industrial and engineering aspects has leads us to the different ways to improve the rate of heat transfer techniques. Domestic refrigerators, automobiles, heat ex-changers, electronic devices, etc. are very few examples where heat transfer is occurring. Hence, it is very important to use suitable techniques to modify the rate of heat transfer and lot of efforts have been made by the different researchers to enhance the rate of heat transfer. In this direction, Choi [7] had made some efforts at the Argonne National Laboratory, USA in 1995, where he suspended the nanoparticles in the base fluids to enhance the thermal conductivity and named a new term "nanofluid". Since, thermal conductivity of the nanofluid is higher hence larger will be the heat transfer rate. There are plenty of researchers which are working on the thermal properties of nanofluids around the globe [14]-[15]. Nanofluids models have been formulated by Eastman et al. [16], Cho and Pak [17] and Xuan and Li [18], Buongiorno in order to understand the convective transport in nanofluids.

Usage of porous medium in an another fascinating techniques to improve heat transfer in industrial systems. Porous medium is a matrix containing voids which have to be filled with fluids so that fluid can flow through these voids. In these days, filling of nanofluids in a porous matrix is gaining ample attention due to its industrial and technological applications. Mahdi et al. [19] reviewed the flow of nanofluids and heat transfer through the porous surfaces. Kasaeian et al. [20] in their article discussed the various models utilized for the simulation of flow of nanofluids through porous surfaces. Nield and Kuznetsov [21], Nield and Kuznetsov [22], Gorla et al. [23], Gorla and Chamkha [24], Nield and Kuznetsov [25] and Mahdy and Ahmed [26] employeed the Buongiorno nanofluid model and utilized the impacts of thermophoresis and Brownian motion to simulate the flow of nanofluid through porous medium. Shermet and Pop [27] discussed the natural convection in the flow of nanofluid through porous cavity. In this study they utilized the Buongiorno's model and concluded that increments in the Lewis number and thermophoresis parameter brought a decrease in the Nusselt number. Sheremet et al. [28] performed a 3D study to understand the flow behavior in the nanofluid saturtaed porous medium for the different values of Lewis and Rayleigh numbers. Various researchers have performed different analysis to

understand the flow of nanofluids through different porous surfaces [29]-[38].

3 Research Gap Identification

As we know that nanofluid is used as a coolant in many industries. It is also called a smart fluid. Nanfluids have various thermo-physical properties such as thermal conductivity, thermal diffusivity, viscosity etc. Nanofluids have enormous applications in sciences and technology. During the survey of literature, we have observed that nanofluids are highly demanding fluids in industrial and technological processes due to their cooling properties. Keeping these cooling properties of nanofluids in mind we have planned to conduct this study. In this research work we will discuss the flow of nanofluid through porous media.

4 Objectives and motivation of the proposed thesis

This research work finds its number of applications in the real world system and act as a motivation for the present research problems. Objectives of this research work are to investigate the flow and heat transfer phenomena of nanofluids in porous media. We will investigate the influence of magnetic field intensity, porous medium permeability, heat source, radiative heat transfer, slip and jump boundary conditions on the flows of nanofluids.

5 Proposed Methodology

At first, we will formulate the mathematical models for the assigned physical problems on the basis of conservation principals of mass, energy, concentration etc. Then we will formulate new models with the help of the existing models. After that the equations which we obtained, can be converted into boundary layer equations by applying the Prandlt boundary layer theory.

Secondly, we will introduce these equations with similarity transformations and applied to highly non linear boundary layer equations to make these governing equations dimensionless.

Thirdly, we will apply numerical methods such as Keller Box Method, Explicit Finite Difference Method. Also we will apply Runge-Kutta Fourth order method. With the help of Runge-Kutta Fourth Order Method on the coupled non linear differential equation to obtain the numerical solutions. The use of Keller Box Method is to obtain the numerical solution which is unconditionally stable and accurate second order. The method is used by various researchers to obtain the numerical solution of parabolic differential equations.

Fourthly, Computational algorithm will be prepared for opted numerical method in symbolic languages (**MATLAB, MATHEMATICA, MAPLE**) in order to solve the highly non linear system of equation.

At last, influence of governing parameters on the numerical results will be presented through graphs, tables and physical interpretation. The obtained results will be presented in details and the influence of controlling parameters will be checked on flow, heat and mass transfer characteristics of Non-Newtonian Fluids.

6 Thesis Outline

This thesis is concerned with the computational analysis of the flow of nanofluids through a porous medium and will contain six chapters as follows:

In **chapter 1** introductory concepts related to boundary layer theory, flow of nanofluids, flow through porous media and solution methodology will be discussed in detail. This will also include the detailed governing equations, adopted nanofluids and porous medium models and numerical procedures.

Chapter 2 will consists literature survey related to flow of nanofluids, heat and mass transfer through porous media.

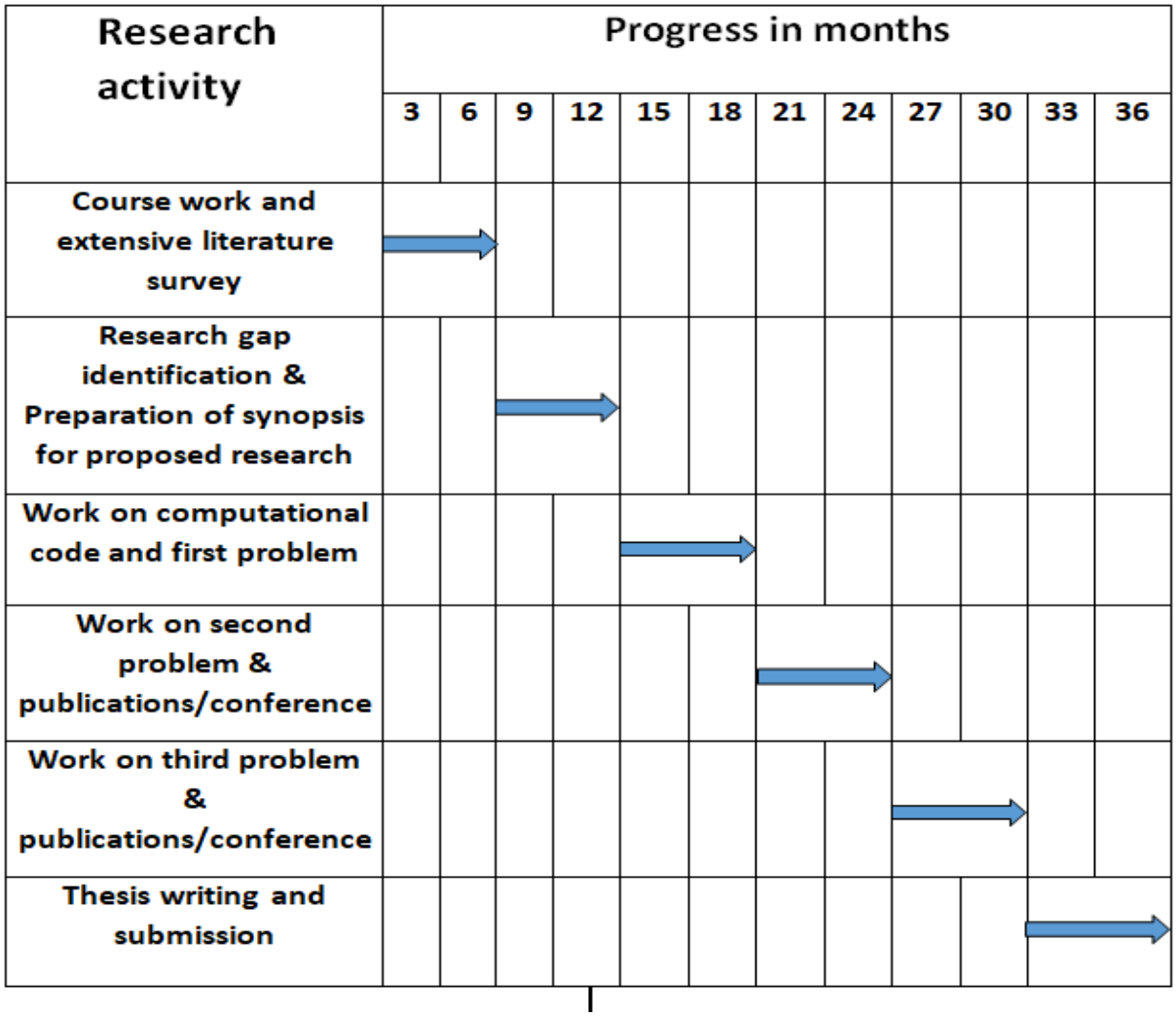
In **chapter 3** we will investigate the flow and heat transfer characteristics of MHD nanofluid through porous medium.

Chapter 4 will comprises the influence of velocity slip and thermal jump on the flow of magnetic nanofluids past a porous medium.

In **chapter 5** we will investigate the impact of radiative heat transfer on the flow of MHD nanofluids through porous medium.

Chapter 6 will be framed to conclude this thesis, and its significance and future work to the researchers.

Research Plan



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